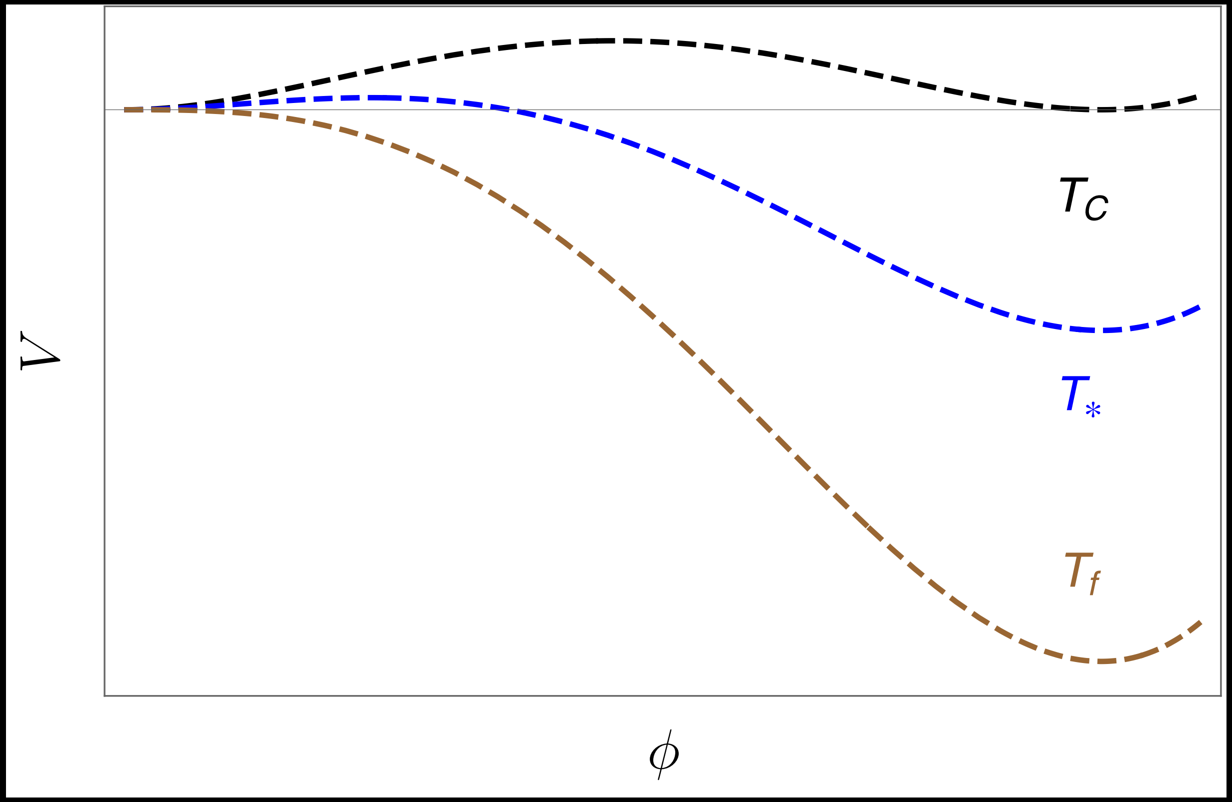
Pulsar timing arrays and sound waves from phase transitions

Graham White (2307.02259) with Tathagata Ghosh, Anish Ghoshal, Huai-Ke Guo, Fazlollah Hajkarim, Stephen King, Kuver Sinha and Xin Wang



$$\Omega = \Omega_{\rm coll} + \Omega_{\rm SW} + \Omega_{\rm turb}$$

Image credit: Tim Dean

$$\Omega = \Omega_{\text{coll}} + \Omega_{\text{SW}} + \Omega_{\text{turb}}$$

Dominates for extremely relativistic walls, $\gamma \sim 10^{14}$

Usually dominates

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May dominate in the UV arXiv:0909.0622

Brief introduction to thermal parameters and expected scale of transition

$$(R_*, T_*, U_f, \tau_{ss}, v_w) \to (\alpha, \beta/H_*, T_*, v_w)$$

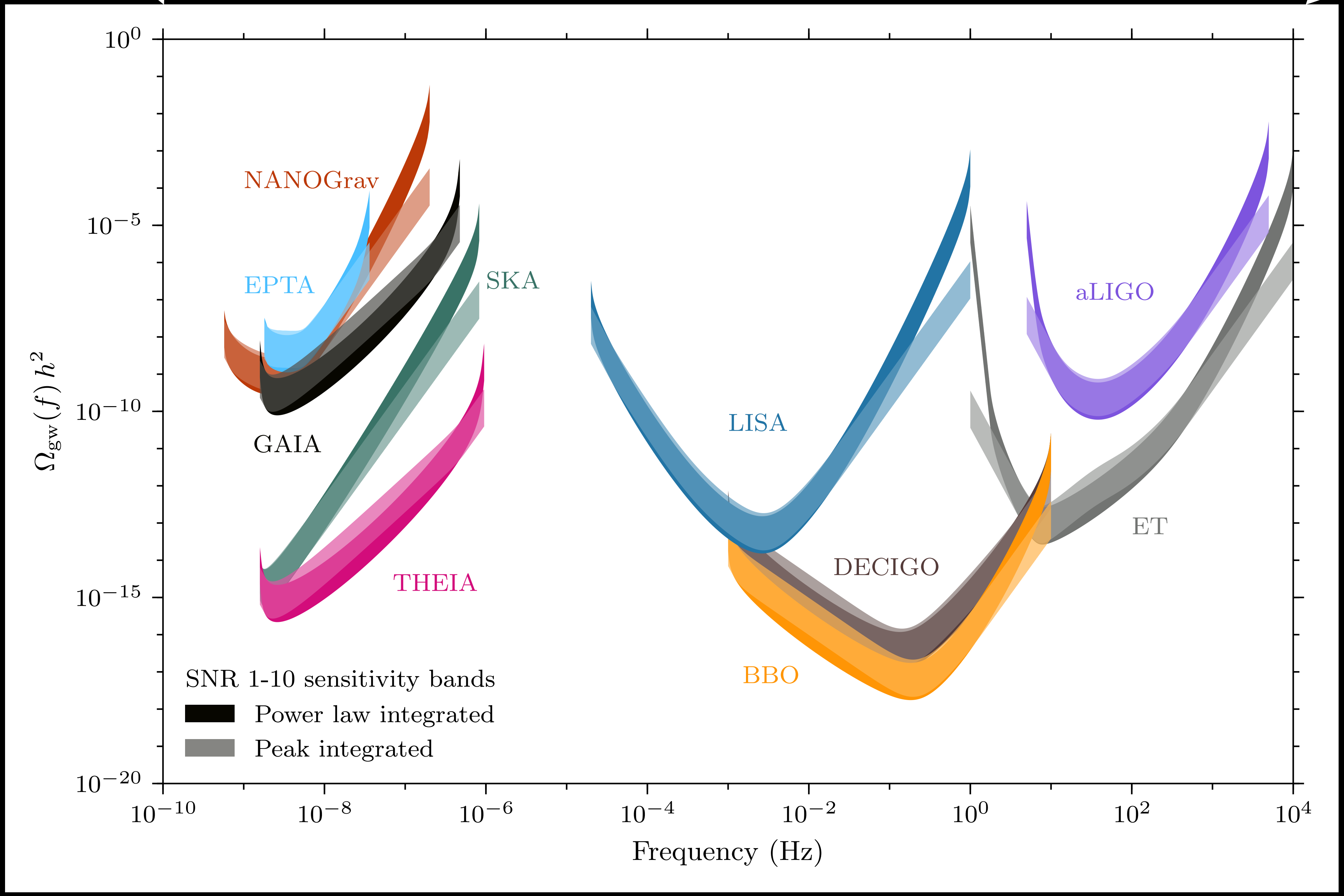
$$\frac{\beta}{H_*} = T\frac{d(S_E/T)}{dT}$$

$$\alpha = \frac{\left(\Delta V - \frac{T}{4}\frac{d\Delta V}{dT}\right)}{\rho_{\rm rad}}$$

Experiment survey: Low to mid frequency

$10^{-9}\text{Hz} \leftrightarrow (10^{-6} - 10^{-2})\text{GeV}$

$10^{4}\text{Hz} \leftrightarrow (10^{7} - 10^{11})\text{GeV}$

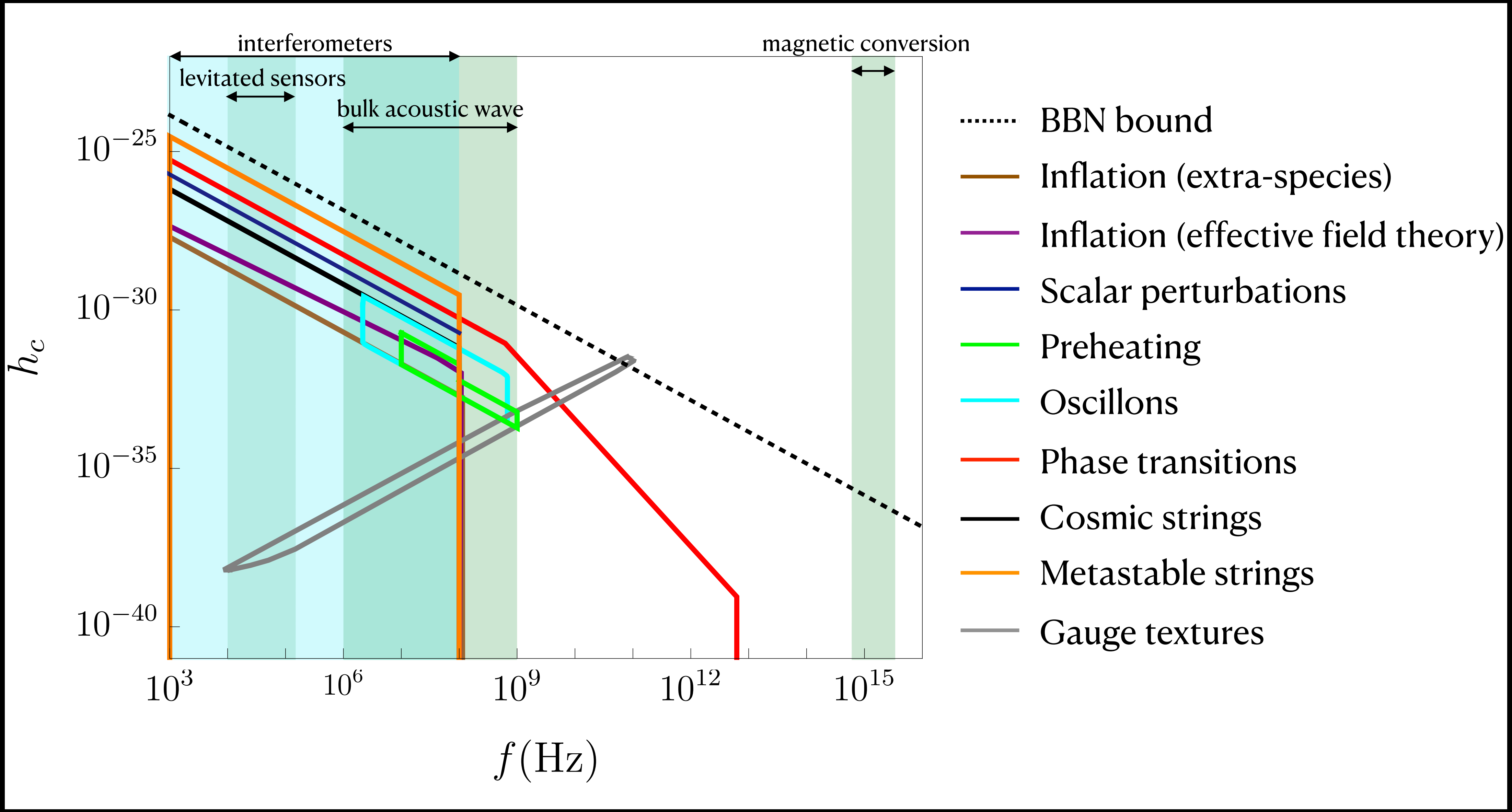


$$f \sim \Lambda(\text{GeV}) \times 10^{-[3,7]}\text{Hz}$$

Garcia-Bellido, Murayama and White 2104.04778

Experiment survey: High frequency

$10^{[6,9]}\text{Hz} \leftrightarrow (10^{[9,16]})\text{GeV} \qquad 10^{15}\text{Hz} \leftrightarrow (10^{[18,\cdots]})\text{GeV}$



$$f \sim \Lambda(\text{GeV}) \times 10^{-[3,7]}\text{Hz}$$

2011.12414

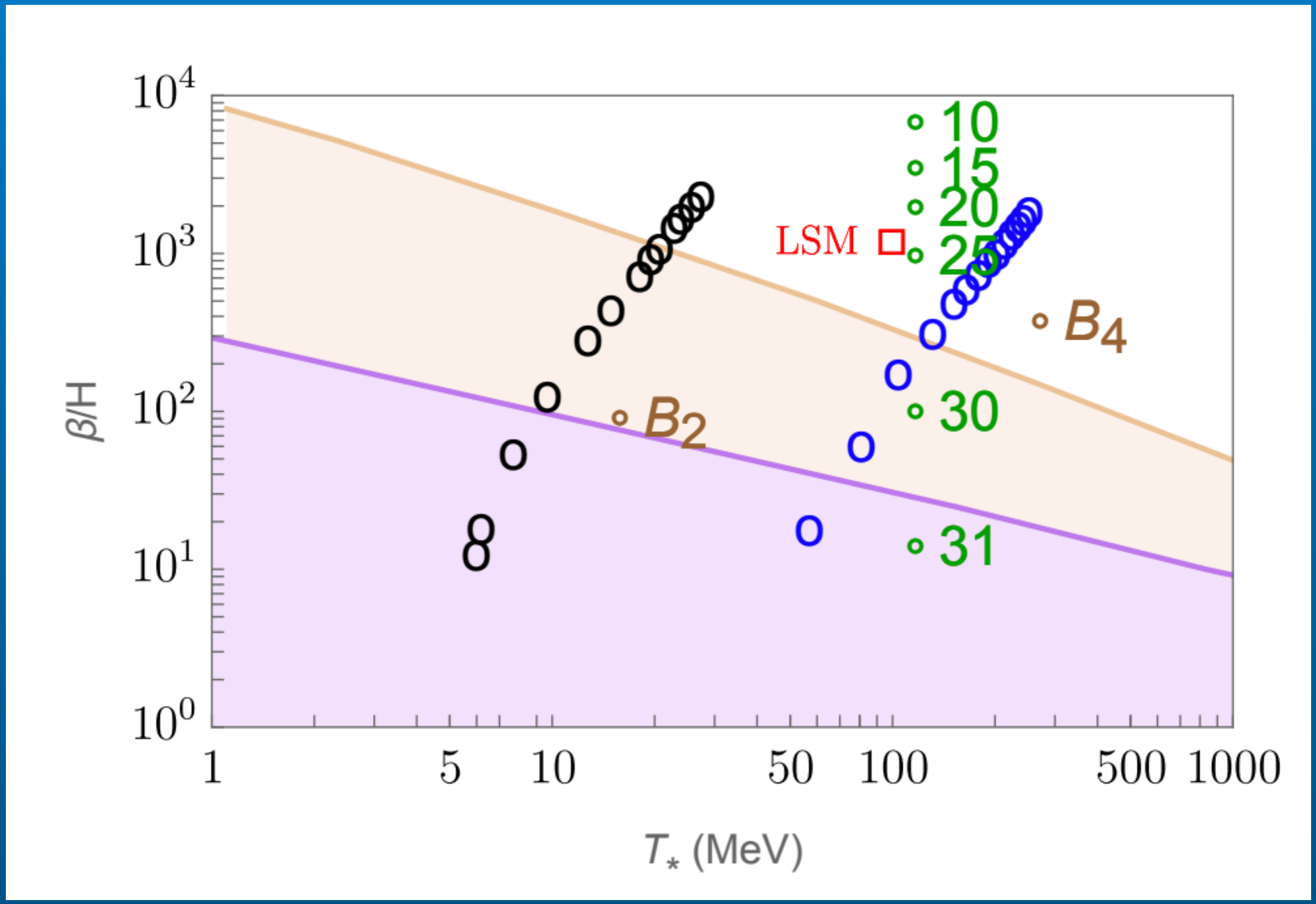
Possible explanations 1) QCD

Expected to be a crossover in a standard picture of cosmology.
QCD transition can be first order if

1) At least one more quark is lighter than expected in the early Universe
2) All quarks are heavier than expected in the early Universe
3) There is a large baryon chemical potential in the Universe
   —Most plausible scenario involves a large lepton asymmetry

Possible explanations 2) Simps chiral pt

Multiple methods of calculation (none of which inspire confidence!)
General expectation that more flavours gives a stronger transition
Hard to get a strong enough transition for 3-4 flavours
Perhaps more flavours would help?



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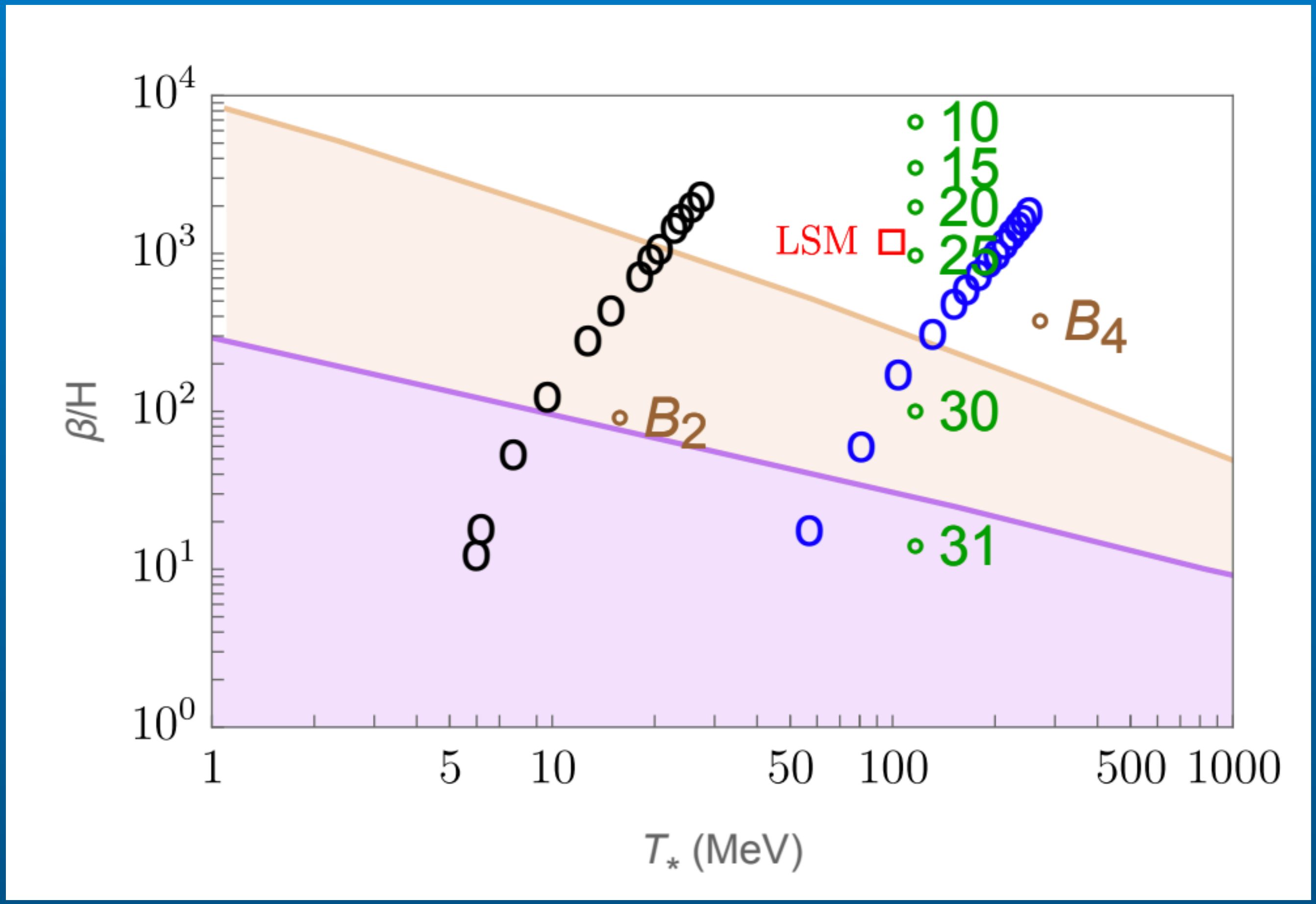
Possible explanations 2) Simps with a glueball pt

-Pretty difficult to be confident of any calculation method
-Can use classical nucleation theory and lattice data as its not clear if anything does better

$$\sigma = (0.013N_C^2 - 0.104)T_C^3, L = \left(0.549 + \frac{0.458}{N_C^2}\right)T_C^4$$



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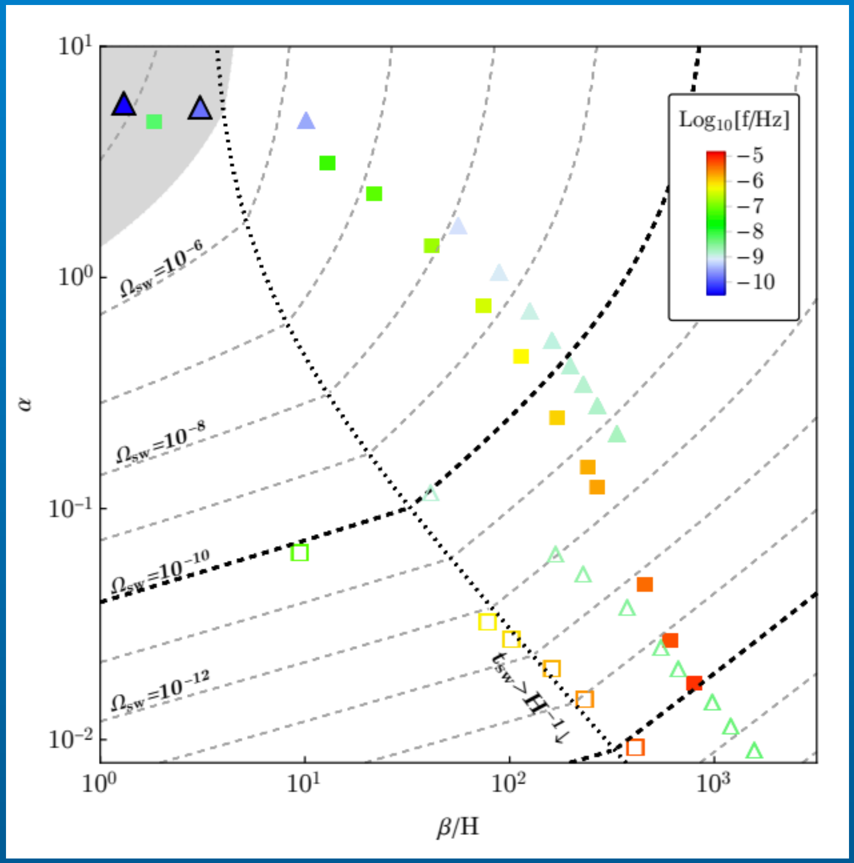
Possible explanations 3) Solitosynthesis

Suppose the scalar field has a global charge and the potential admits a Q-ball solution - potential changes slower than quadratic for some period



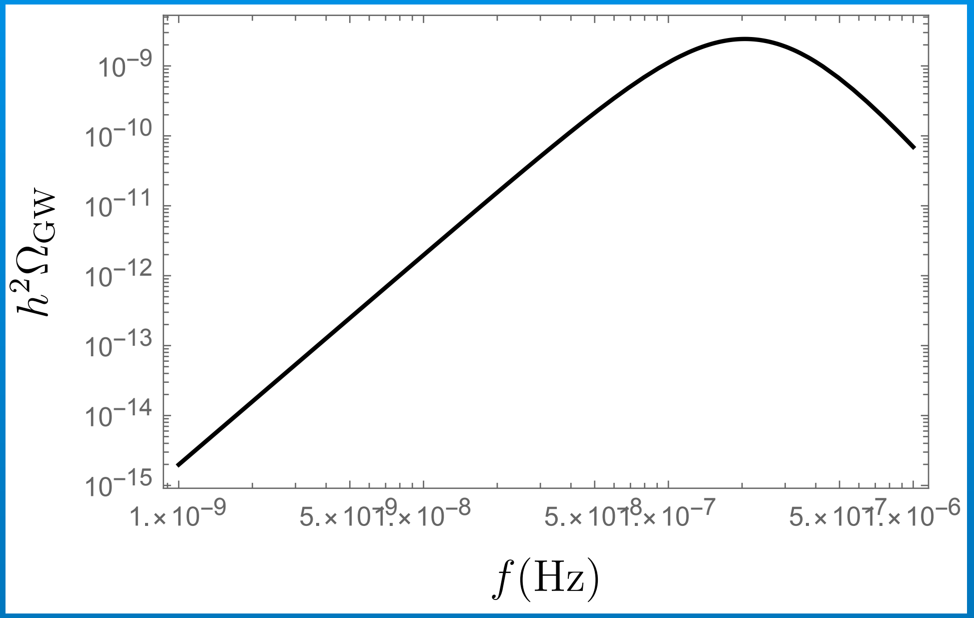
1910.09562

Sound shell model fit

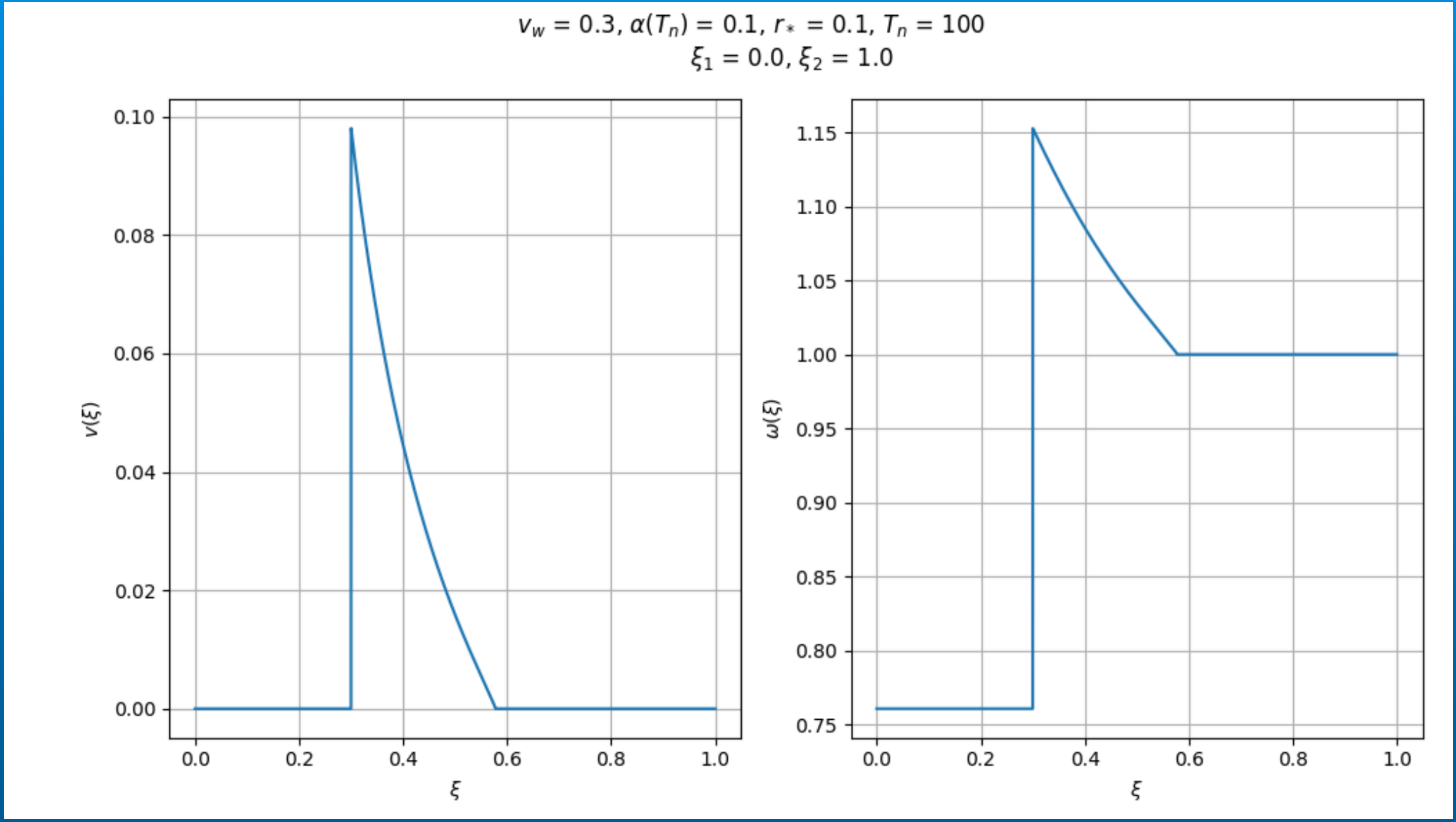
$$\Omega_{\rm GW} = \Omega_p(\alpha, \beta, T_*, \alpha) S(x)$$

$$x = f/f_p$$

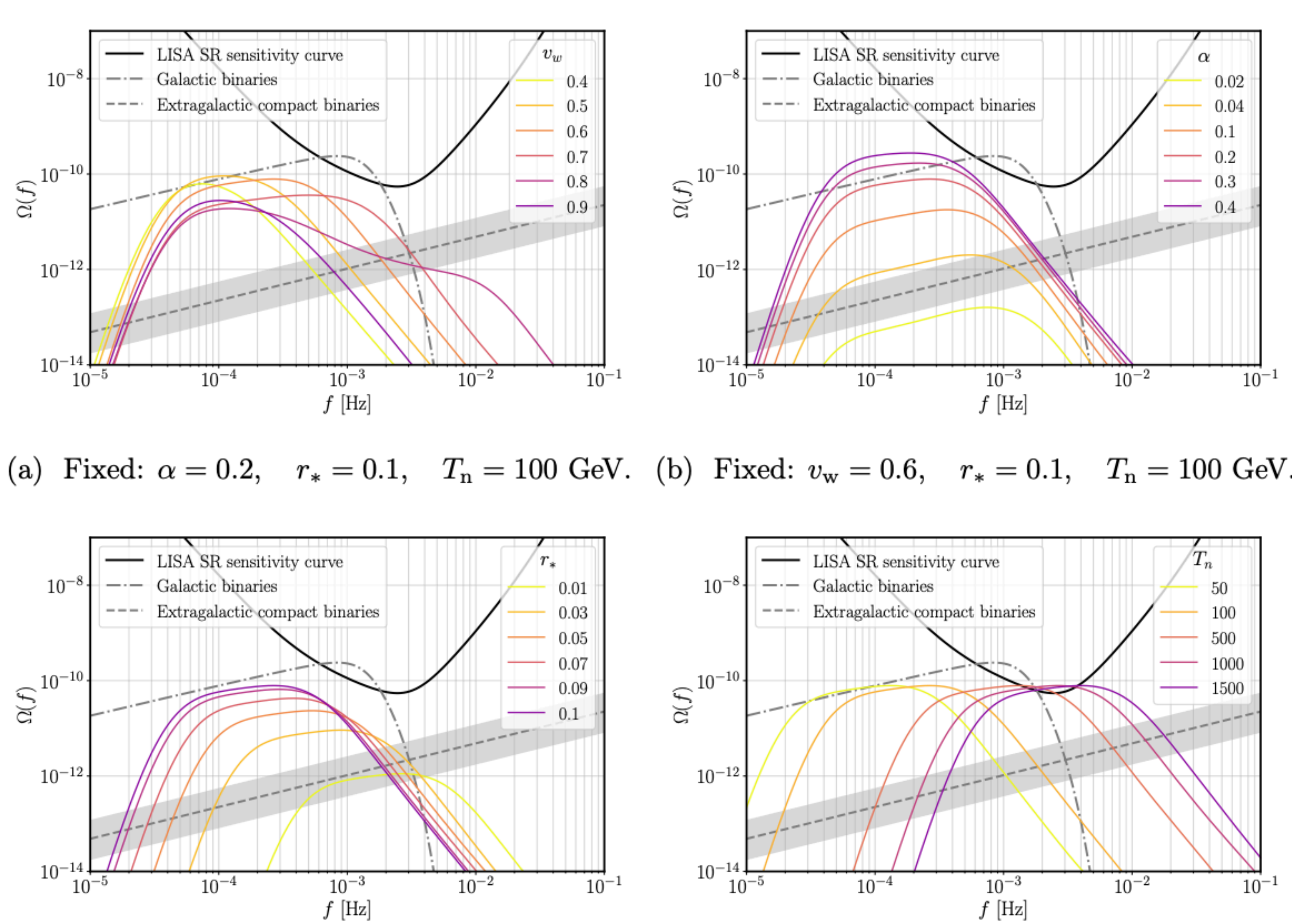
$$S(x) = x^3 \left(\frac{7}{4 + 3x^2} \right)$$



Sound shell model model in detail - velocity profiles



Sound shell model model in detail - double broken power laws

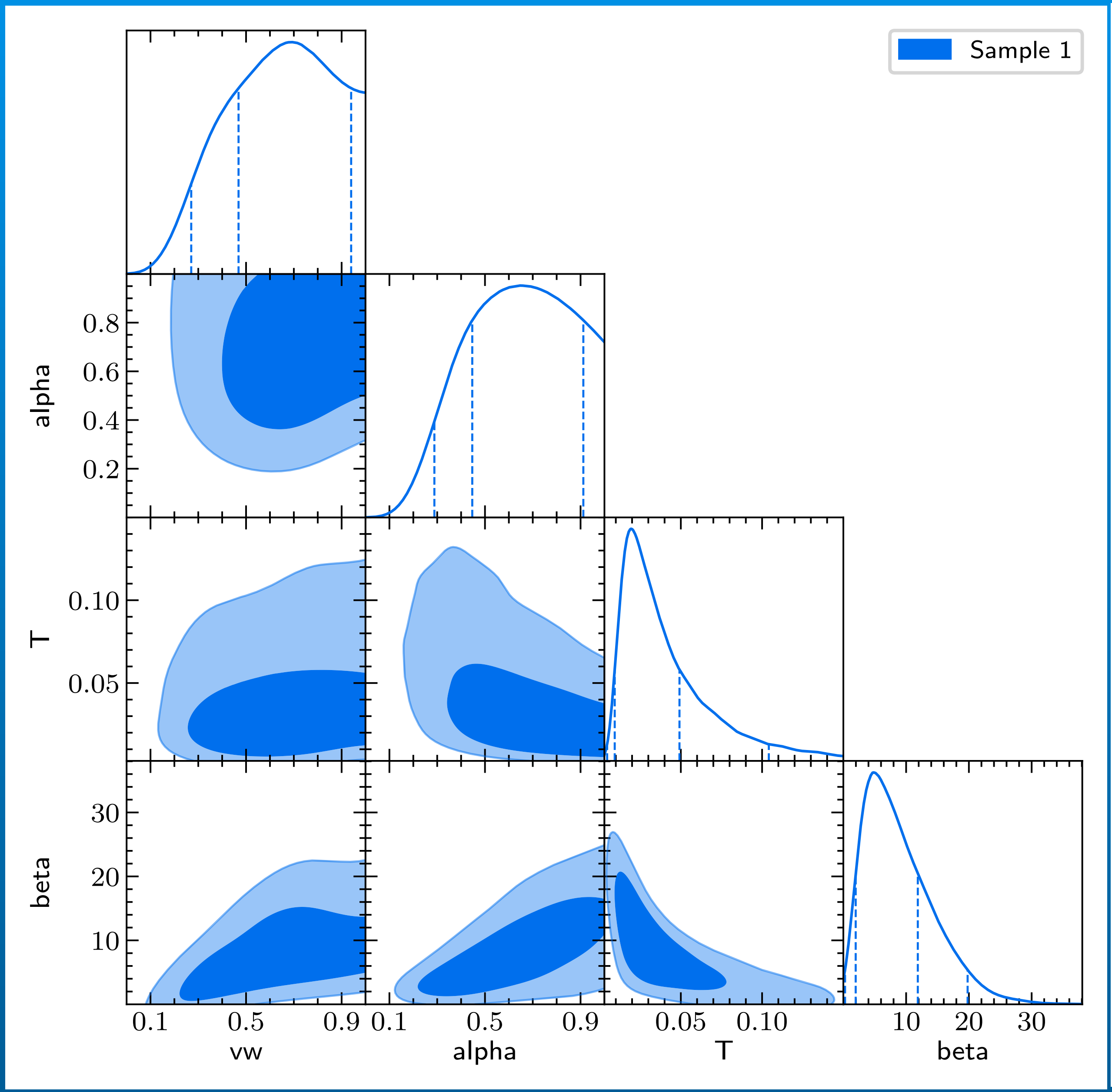


(a) Fixed: $\alpha = 0.2$, $r_* = 0.1$, $T_\mathrm{n} = 100$ GeV. (b) Fixed: $v_\mathrm{w} = 0.6$, $r_* = 0.1$, $T_\mathrm{n} = 100$ GeV.

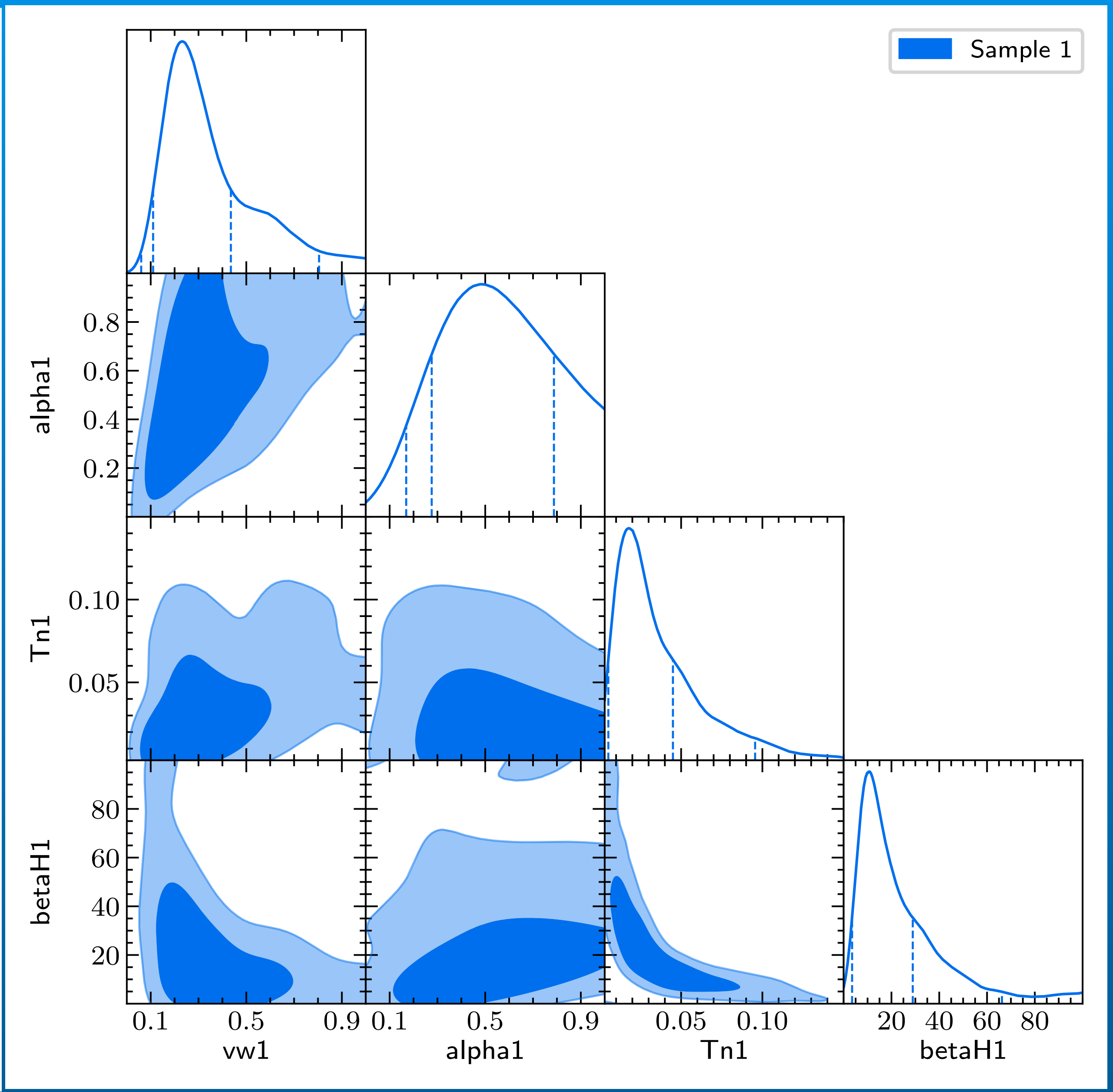
(c) Fixed: $v_\mathrm{w} = 0.6$, $\alpha = 0.2$, $T_\mathrm{n} = 100$ GeV. (d) Fixed: $v_\mathrm{w} = 0.6$, $\alpha = 0.2$, $r_* = 0.1$.

2106.05984

Sound shell model in detail - posterior distributions

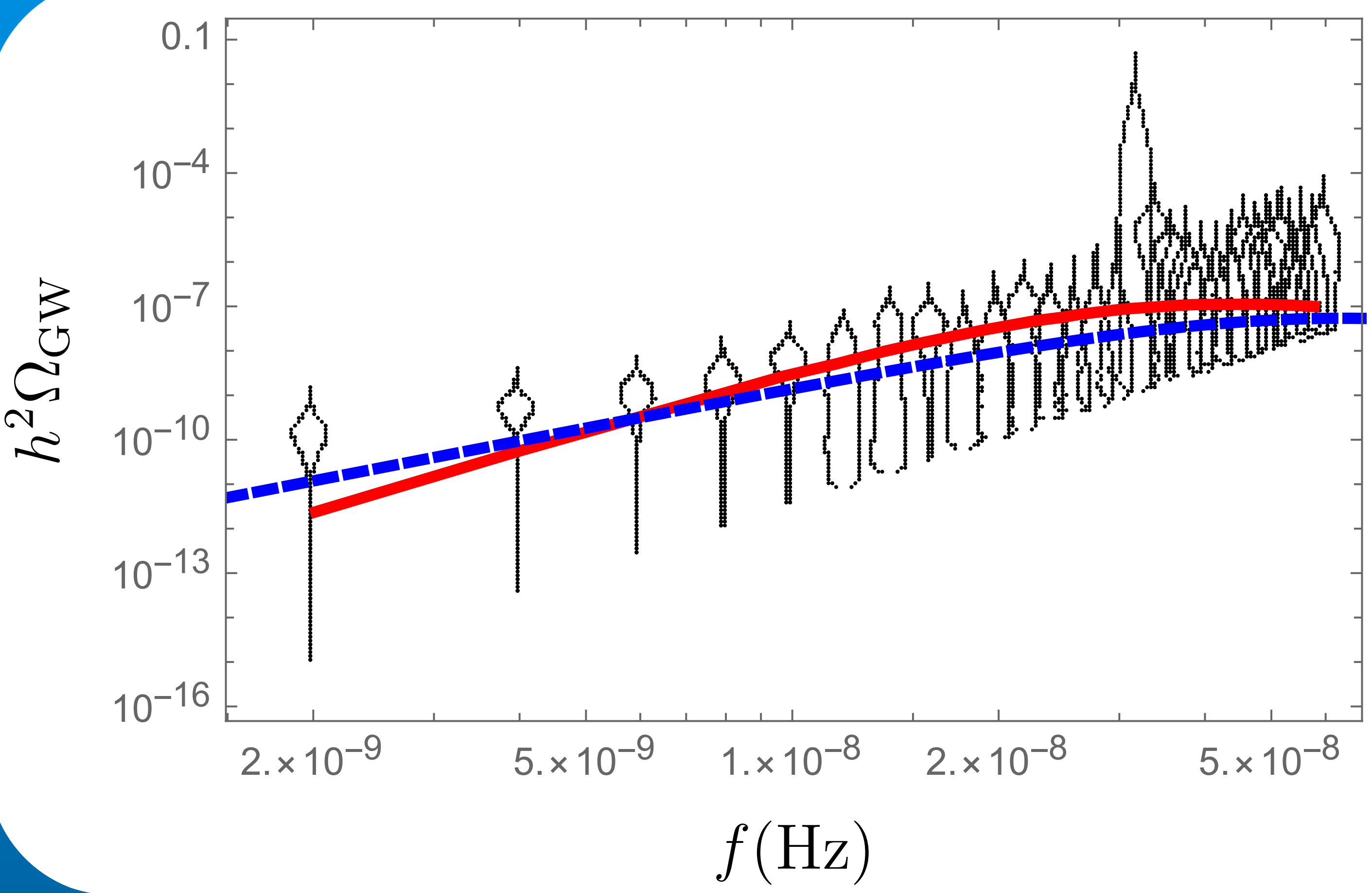


Analytic broken power law fit



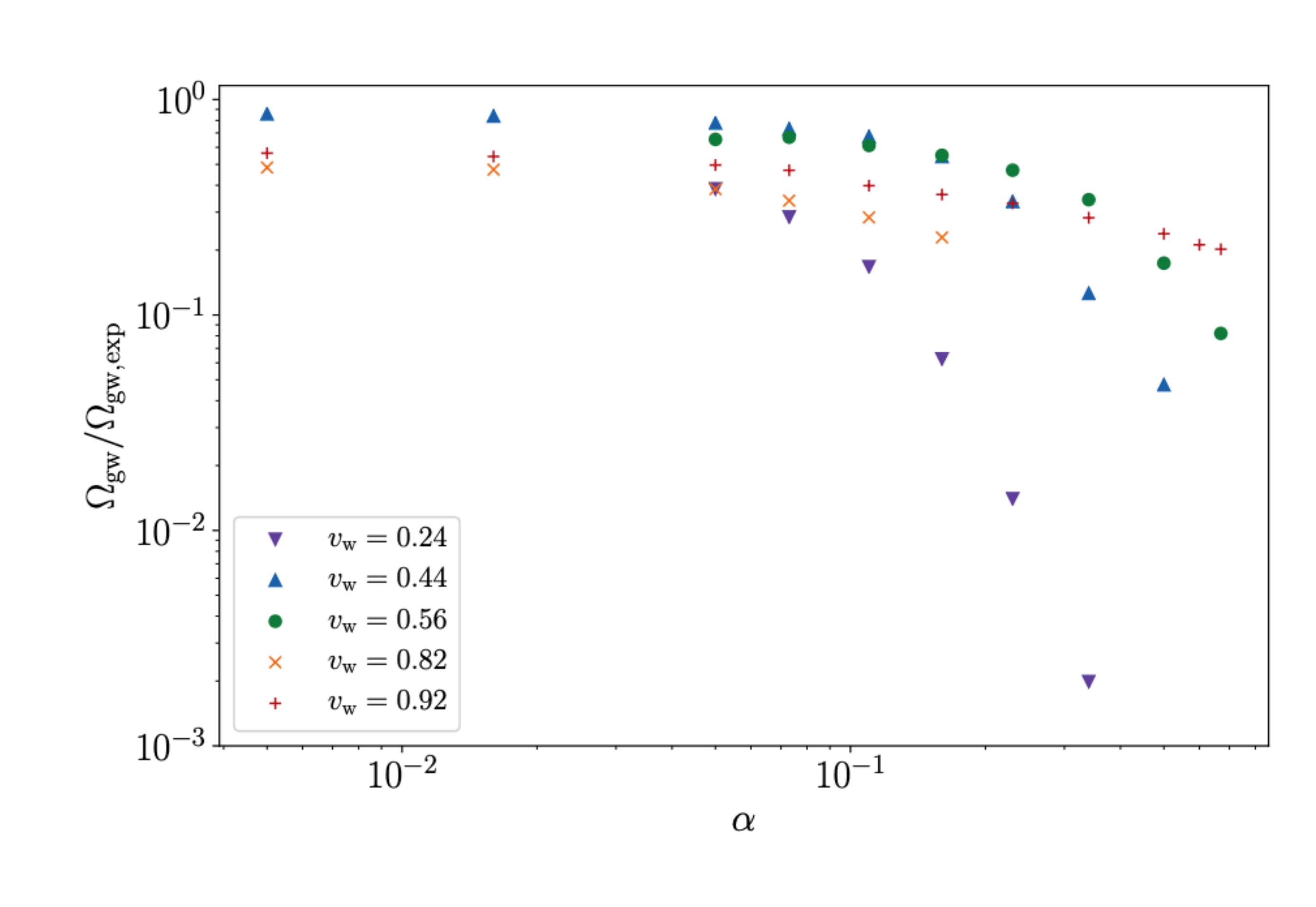
Double broken power law

Sound shell model in detail - best fits



Bayes factor forth coming

Theoretical errors - vorticity



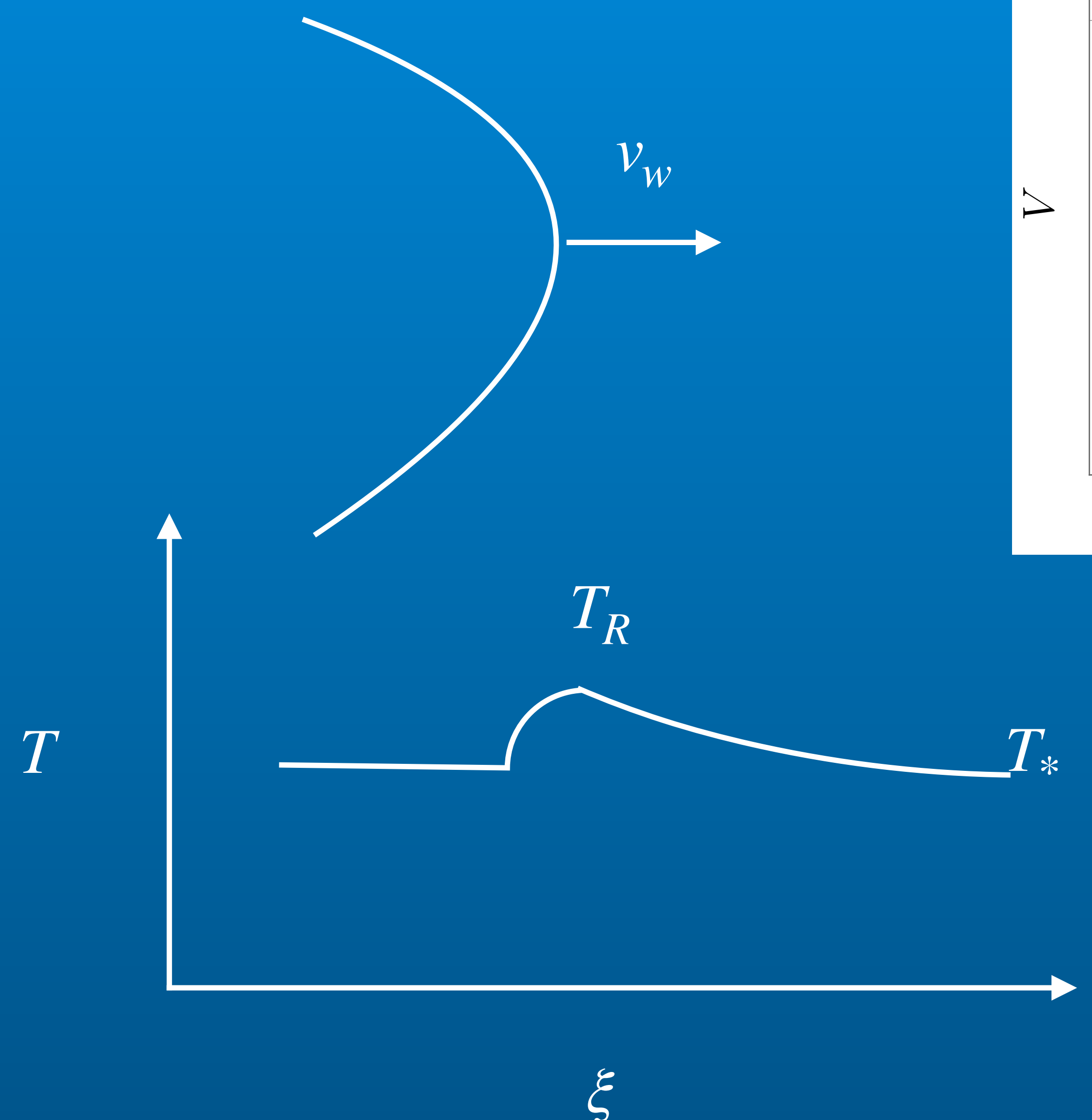
From 1906.00480

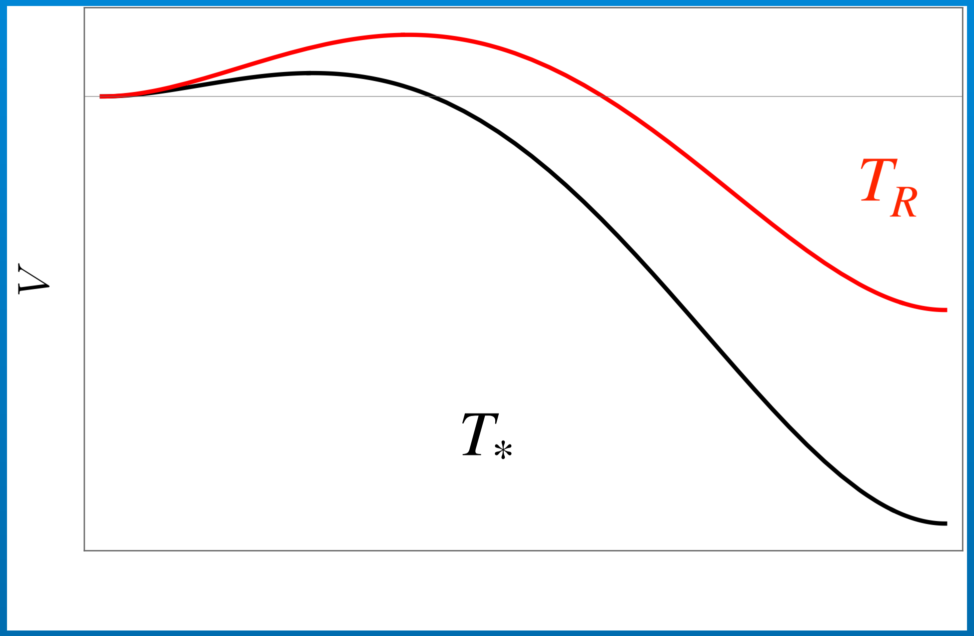
Theoretical errors - beyond the bag

From 2004.06995 no longer treat speed of sound as constant

- **Very small change to broken power law typically**
- **Could be a more dramatic change to velocity profile shape and therefore the shape of the spectrum**

Theoretical errors - reheating





Conclusions

Plenty of motivation for a phase transition at the ~ QCD scale or slightly below
More careful calculation of the soundshell leads to a better fit with more realistic thermal parameters
Vorticity and reheating considerations could alter this picture